PAPER Special Section on Parallel and Distributed Computing and Networking

SP-MAC: A Media Access Control Method Based on the Synchronization Phenomena of Coupled Oscillators over WLAN*

Hiroyasu OBATA^{†a)}, Member, Ryo HAMAMOTO^{†b)}, Student Member, Chisa TAKANO^{†c)}, and Kenji ISHIDA^{†d)}, Members

SUMMARY Wireless local area networks (LANs) based on the IEEE802.11 standard usually use carrier sense multiple access with collision avoidance (CSMA/CA) for media access control. However, in CSMA/CA, if the number of wireless terminals increases, the back-off time derived by the initial contention window (CW) tends to conflict among wireless terminals. Consequently, a data frame collision often occurs, which sometimes causes the degradation of the total throughput in the transport layer protocols. In this study, to improve the total throughput, we propose a new media access control method, SP-MAC, which is based on the synchronization phenomena of coupled oscillators. Moreover, this study shows that SP-MAC drastically decreases the data frame collision probability and improves the total throughput when compared with the original CSMA/CA method.

key words: wireless LAN, SP-MAC, synchronization phenomena of coupled oscillators, Kuramoto model, media access control

1. Introduction

The rapid spread of mobile terminals, such as smartphones and tablet devices, is increasing the usage of wireless LANs based on IEEE802.11 [1]. IEEE802.11 adopts carrier sense multiple access with collision avoidance (CSMA/CA) as the media access control (MAC). To avoid data frame collisions, CSMA/CA uses the random differing time (back-off time) derived using a random integer in the contention window (CW). However, if the number of wireless terminals connecting an access point (AP) increases, the back-off time derived by the initial CW tends to conflict among wireless terminals. Consequently, a data frame collision often occurs, which causes the degradation of the total throughput in the transport layer protocols (UDP and TCP). In this study, we assumed that the number of wireless LAN terminals dramatically increases. Therefore, to provide stable and tolerant wireless LAN services in the future, it is expected that collision avoidance will become one of the critical problems to overcome in wireless LAN networks.

To avoid data frame collisions, several kinds of methods can be used such as point coordination function (PCF)

Manuscript received December 24, 2014.

Manuscript revised May 13, 2015.

c) E-mail: takano@hiroshima-cu.ac.jp

methods [1], [2] and time division multiple access (TDMA) methods [3]-[7]. However, these methods always need to control the access timing at the AP. Furthermore, some studies [8], [9] use a method in which each terminal autonomously avoids data transmission conflicts. However, because the methods used in these studies [8], [9] always need to send the control packets to avoid the collision, it is expected that the overhead increases with the number of wireless terminals. Consequently, the total throughput decreases when there are numerous wireless terminals. In addition, there are several resource reservation methods [10]-[13] based on CSMA/CA [14]. Because these methods are based on CSMA/CA, they are compatible with the CSMA/CA terminals. However, these methods require that each wireless terminal needs extra procedures for reserving resources and avoiding collisions; for example, sending the current status and measuring the status of other terminals.

In this study, to improve the total throughput by avoiding data frame collisions, we propose a new MAC method, SP-MAC, which is based on the synchronization phenomena^[15] of coupled oscillators. The key concept of our method is to calculate the back-off time using the synchronized phase with phase shifting instead of the random integer in the original CSMA/CA method. Moreover, each terminal independently calculates the synchronized phase with phase shifting after receiving a control packet from the AP at the beginning of data transmission. Thus, all terminals can avoid data frame collisions. Next, we evaluated the performance of SP-MAC using simulation experiments. The simulations confirmed that SP-MAC can drastically decrease the probability of data frame collisions and improve the total throughput when compared with the original CSMA/CA method. Furthermore, we found that SP-MAC can effectively use the bandwidth when the number of terminals increases by avoiding data frame collisions.

The rest of this paper is structured as follows. We describe the IEEE802.11 wireless LAN, the synchronization phenomena of coupled oscillators, and existing methods in Sect. 2. In Sect. 3, we explain the proposed method (SP-MAC) based on the synchronization phenomena of coupled oscillators. Section 4 presents the evaluations and discussions of the results obtained from simulation experiments. Finally, we summarize the paper in Sect. 5.

Manuscript publicized September 15, 2015.

[†]The authors are with the Graduate School of Information Sciences, Hiroshima City University, Hiroshima-shi, 731–3194 Japan. ^{*}An earlier version of this paper was presented at ASON'14 [28].

a) E-mail: obata@hiroshima-cu.ac.jp

b) E-mail: ryo@net.info.hiroshima-cu.ac.jp

d) E-mail: ishida@hiroshima-cu.ac.jp

DOI: 10.1587/transinf.2015PAP0004

2. Related Works

This section presents an overview of the IEEE802.11 wireless LAN and the model for the synchronization phenomena of coupled oscillators. Moreover, we describe the existing methods for avoiding data frame collisions over wireless LAN.

2.1 IEEE802.11 Wireless LAN

The IEEE802.11 wireless LAN is one of the most popular standards for wireless Internet access. It has several versions such as IEEE802.11b [16], IEEE802.11g [17], IEEE802.11n [18], and IEEE802.11ac [19]. These versions use 2.4 GHz and 5 GHz bands.

In IEEE802.11 wireless LAN networks, a wireless terminal uses CSMA/CA as the MAC and autonomously sends data frames. Thus, each wireless terminal individually decides the timing of data transmission. In CSMA/CA, if the channel becomes idle when a data frame arrives in the transmission queue, it defers to DCF inter frame space (DIFS) time. Then, if the channel remains idle after DIFS, CSMA/CA waits for the back-off time, which is randomly calculated using a CW. Subsequently, if the channel remains idle after the back-off time, the terminal sends the data frame. The back-off time is determined using Eq. (1), which is calculated independently by each terminal.

$$Backoff = Random() \times SlotTime \tag{1}$$

In Eq. (1), *Random*() and *SlotTime* indicate a random integer derived from a discrete uniform distribution [0,CW] and the slot time interval specified in IEEE802.11, respectively. At this point, the initial CW is set to CW_{min} . If a collision causes the data frame transmission to fail, then the terminal sets the back-off time using Eq. (1) again. In this case, the CW becomes twice as large as the previous value, and the upper bound is CW_{max} . If the retransmission exceeds the maximum retry limits (usually 7), the terminal discards the data frame.

2.2 Synchronization Model of Coupled Oscillators

Synchronization indicates that the phenomena caused by multiple oscillators with different periods transform incoherent rhythms into synchronized ones with each interaction. This phenomena is also observed in nature such as the synchronous flashing of fireflies [20] and the synchronization of metronomes [21]. These synchronized oscillators are called coupled oscillators. During the synchronization, the phase differences and frequencies of all the coupled oscillators converge at certain values.

Several studies [22]–[24] discuss the synchronization phenomena, and have proposed mathematical models for this phenomena. Additionally, another study [25] has demonstrated the synchronization phenomena based on the synchronization model in a real environment. One of the typical models is the Kuramoto model [26]. In this paper, we explain the synchronization of *N* coupled oscillators using the Kuramoto model. In the Kuramoto model, the *i*-th oscillator runs independently at its own natural frequency ω_i and interacts with all the others. Then, the *i*-th oscillator's phase θ_i ($0 < \theta \le 2\pi$) is calculated using Eq. (2).

$$\frac{\mathrm{d}\theta_i}{\mathrm{d}t} = \omega_i + \frac{K}{N} \sum_{j=1}^N \sin(\theta_j - \theta_i) \quad (i = 1, 2, \cdots, N) \quad (2)$$

In Eq. (2), K(> 0) indicates coupling strength. The second term is an interaction term, which is standardized by K/N to be independent from system size N.

In addition, a mathematical analysis [26] is performed using the mean field theory when numerous oscillators synchronize. The mean field is determined using Eq. (3).

$$Z = \frac{1}{N} \sum_{j=1}^{N} \exp(i\theta_j(t)) \equiv R \exp(i\Theta)$$
(3)

In Eq. (3), R ($0 \le R \le 1$) and Θ ($0 < \Theta \le 2\pi$) indicate the amplitude and phase in the mean field, respectively. In addition, *i* denotes an imaginary unit in Eq. (3). The mean field *Z* is called an order parameter and is used as a synchronization index. If a collective synchronization occurs, the amplitude *R* has a constant value and the phase Θ describes a linear increase, such as $\Theta = \Omega t$. Ω is the collective frequency. When *R* is 0, synchronization does not occur. On the other hand, as *R* increases close to 1, the synchronization level is strong.

Next, in the Kuramoto model, Eq. (2), *K* has to satisfy Eq. (4) for collective synchronization.

$$K > K_c$$

$$K_c = \frac{2}{\pi g(\omega_0)}$$
(4)

In Eq. (4), K_c and $g(\omega_0)$ are the critical coupling strength and density function of a natural frequency (i.e., the symmetric function with ω_0 as the center of all ω), respectively. For example, if the natural frequency ω has a uniform distribution in $[\alpha, \beta]$, the density function is derived using $g(\omega_0) = (\beta - \alpha)^{-1}$. In this case, the critical coupling strength is determined using Eq. (5).

$$K_c = \frac{2(\beta - \alpha)}{\pi} \tag{5}$$

Note that this is a theoretical threshold when there are infinitely several oscillators. Therefore, we have to carefully calculate K_c .

2.3 Existing Media Access Controls

This section explains the existing MACs for collision avoidance.

First, the typical collision avoidance methods are IEEE802.11 PCF and its modified method [2]. These methods can avoid data frame collisions because the AP controls

the access timing of all wireless terminals using a polling frame. However, if multiple APs use the same channel, the transmission of polling frames can fail among APs because each AP does not synchronize the transmission timing of polling frames. In this situation, the wireless terminal cannot send data. In addition, because IEEE802.11 PCF is the option function, DCF and PCF are alternately used. Therefore, the collision occurs in a DCF period even if PCF is used.

The other collision avoidance method is a TDMAbased method [3]–[7]. In TDMA, each slot time is applied to the wireless terminal. Then, even if the number of wireless terminals increases, no collision occurs. However, the TDMA-based method needs to strictly synchronize the clock among all wireless terminals. Moreover, the central terminal always needs to maintain the detailed time slot of all wireless terminals, and this method cannot coexist with CSMA/CA terminals.

Some studies [8], [9] have proposed a phase diffusion time division (PDTD) method that autonomously avoids the conflict of data transmission timing. PDTD is developed for wireless sensor networks and is based on the dynamics of coupled phase oscillators among peripheral terminals. In PDTD, each terminal exchanges control information (including the coupled phase dynamics [9]) within two-hop neighbor terminals and calculates the communication timing using this information. Another study [27] has demonstrated the synchronization phenomena by implementing the PDTD in a real environment. However, PDTD always needs to send control packets between two-hop neighbor terminals to maintain a collision-free state. Therefore, the number of control packets (overhead) increases as the number of wireless terminals increases. The total throughput is expected to decrease as the number of terminals increases. Furthermore, this method cannot be used when CSMA/CA terminals coexist because CSMA/CA terminals do not transfer control packets.

Finally, some studies [10]–[13] have proposed a resource reservation method based on CSMA/CA [14]. First, [10] proposed a method using the modified RTS to reserve bandwidth. However, this method needs to overhear the modified RTS from other wireless terminals. Moreover, because RTS/CTS increases the overhead, the available bandwidth becomes smaller. Next, EBA [11] and CSMAC [12] try to reserve the time slot for a data frame transmission at the AP. In these methods, to avoid collision among the wireless terminals, the AP adjusts the CW for each wireless terminal based on the next CW value that is sent by each wireless terminal and notifies the terminal of the adjusted CW. Then, each wireless terminal uses the data frame using the adjusted CW. However, these methods need to send the next CW to all wireless terminals and the AP has to synchronize the clock with all the wireless terminals. Finally, [13] proposes a method, Semi-Random Backoff (SRB), that reuses a time slot in the consecutive back-off cycles. In this method, after successful transmission using the random value based on the CW, the successful wireless terminals use the deter-



Fig.1 Example: cosine curves of synchronized oscillators with phase shifting.

ministic value based on the previous random value for the next transmission. Thus, the wireless terminal sends a data frame using the deterministic back-off time based on the previous one that does not conflict with the other wireless terminals. However, this method needs to estimate the number of busy slots for setting the back-off time. Therefore, if the estimation fails, it is possible that this method would not work effectively. In summary, the existing resource reservation methods require that each wireless terminal needs extra procedures for reserving resources and avoiding collisions. Therefore, this paper proposes a new method that does not require the wireless terminal to send the extra control frame and observe the transmission status.

3. SP-MAC: A Media Access Control Method Based on the Synchronization Phenomena of Coupled Oscillators

This section explains the proposed MAC method (SP-MAC) based on the synchronization phenomena of coupled oscillators.

3.1 Overview

As mentioned in Sect. 2.1, CSMA/CA in the IEEE802.11 standard calculates the back-off time using a random integer derived from the discrete uniform distribution [0, CW]. SP-MAC uses the synchronized phase based on Eq. (2) for setting the back-off time instead of using a random integer. It should be noted that all the oscillators synchronize with phase shifting. Figure 1 shows an example of cosine curves that result when four oscillators synchronize with phase shifting. Each cosine curve indicates the phase of each oscillator. When all the oscillators synchronize with phase shifting, each oscillator has a different $\cos \theta_i(t)$ at time *t*. After a certain time Δt passes $(t + \Delta t)$, the relationship of $\cos \theta_i(t)$ changes; for example, $\cos \theta_1(t) > \cos \theta_4(t)$ and $\cos \theta_1(t + \Delta t) < \cos \theta_4(t + \Delta t)$. Therefore, it is expected that

SP-MAC can avoid the overlap of back-off time among terminals using these synchronized phases with phase shifting.

For our study, we set the following preconditions.

- The AP and all wireless terminals do not move.
- The AP and all wireless terminals implement SP-MAC.
- The AP and all wireless terminals stop using the RTS/CTS function (i.e., they do not send RTS/CTS).
- 3.2 Detailed Procedures of SP-MAC

This section presents the details of the procedures for the AP and wireless terminals in SP-MAC.

Initially, the AP determines the control parameters in advance. Then, it sends the parameters to all wireless terminals at the beginning of the data transmission.

Procedures at AP

- 1. The AP determines the number of connected wireless terminals N based on the number of connection requests from wireless terminals.
- 2. The AP determines the natural frequency ω_i and coupling strength *K*, which satisfy the synchronizing condition according to *N* (see Sect. 2.2). To lead the condition that each oscillator synchronizes with phase shifting, the AP adopts a different ω_i for each wireless terminal (i.e., there is no overlap among all ω_i). Next, the AP sets an ID *i* ($1 \le i \le N$), which identifies each wireless terminal. Then, the AP applies ω_i and an initial phase $\theta_i(0)$ to the *i*-th wireless terminal. Each initial phase $\theta_i(0)$ has a different value to avoid the collision at the beginning of the data transmission.
- 3. Using a beacon, the AP sends the control parameters, which include *i*, $\theta_i(0)$, ω_i , *K*, a control interval Δt , and *N* for all wireless terminals.
- 4. After sending the beacon, if the AP receives a data frame from a wireless terminal, it sends an ack frame in the same manner as the original CSMA/CA method.
- 5. If the number of wireless terminals changes after each wireless terminal starts data transmission, the AP modifies the control parameters based on *N* and sends them using a beacon again.

Then, each wireless terminal works as follows after receiving the beacon.

Procedures at Wireless Terminal

1. After receiving the beacon, the wireless terminal immediately starts calculating the phase using the control parameters. Next, the wireless terminal calculates the phase $\theta_i(t)$ for all ID *i* using Eq. (2) for every Δt . The phase calculation continues, even if there is no data for transmission while connecting to the AP. If the wireless terminal receives a beacon including the control parameters from the AP again, it uses the control parameters

Algorithm	1	Procedures	at	AP.
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Require: N \ge 0
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- 1: Set *K* and ω_i based on *N* for a terminal *i*
- 2: Send $(i, \theta_i(0), \omega_i, K, \Delta t, N)$ by using beacon
- 3: **loop**
- 4: **if** Receive a data frame from the terminal **then**
- 5: Send an ack frame for the terminal
- 6: end if
- 7: if The number of wireless terminals changes then
- 8: goto 1 :
- 9: end if
- 10: end loop

in the latest beacon.

2. If data arrives from the upper layer at time *t*, the wireless terminal calculates the back-off time *Backoff* using Eq. (6) and the phase $\theta_i(t)$ for each ID *i*. In Eq. (6), *S lotTime* and α show the slot time interval specified in IEEE802.11 and a coefficient for obtaining the normalized phase, respectively. In this study, we set α equal to 100^{\dagger} .

$$Backoff = ((|\cos \theta_i(t)| \times \alpha) \mod N) \times S \ lotTime$$
(6)

3. When the channel remains idle after DIFS and the back-off time, the wireless terminal sends a data frame, which is the same as the one used in the original CSMA/CA method. If the wireless terminal detects data frame collisions, it calculates the new back-off time using Eq. (6) and the phase when the collision is detected again. Then, the wireless terminal retransmits the data frame.

The abovementioned procedures are summarized in Algorithm 1 and Algorithm 2. If the AP needs to send data, i.e., there is a downlink flow from the AP to the wireless terminal, it uses one of the phases and repeats the same procedures at wireless terminals. Therefore, the downlink flow can coexist with the uplink flow.

SP-MAC only sends the control parameters for calculating the phase at the beginning of transmission when the number of wireless terminals does not change. Hence, each wireless terminal works autonomously based on the model for the synchronization phenomena of coupled oscillators. Furthermore, because SP-MAC is based on the original CSMA/CA (i.e., only the calculation of back-off time at the wireless terminal is different), it can be used for an environment where both the SP-MAC terminals and the original CSMA/CA terminals exist [28].

4. Simulation Experiments

In this section, we discuss how we evaluated SP-MAC using

[†]This paper adopts $\alpha = 100$ for setting the time scale of the back-off time equal to the one used with the CSMA/CA method. Moreover, because we focus on basic performance, the detailed discussion regarding α includes future work.

Algorithm 2 Procedures at wireless terminal.

Require: $i, \theta_i(0), \omega_i, K, \Delta t, N$ 1: $time_{current} \leftarrow 0$ 2: $calc_{interval} \leftarrow \Delta t$ 3: loop 4: if *time_{current}* > *calc_{interval}* then 5: for all $i (1 \le i \le N)$ do 6: Calculate $\theta_i(t)$ using Eq. (2) 7. end for 8. $calc_{interval} \leftarrow calc_{interval} + \Delta t$ 9: end if 10: if The terminal wants to send a data frame then Calculate Back-off time using Eq. (6) 11: 12. Send a data frame after DIFS and Back-off time 13: end if if Detect collision at time current then 14: 15. Calculate Back-off time using Eq. (6) at time current 16: goto 12 : 17: end if if Receives a beacon including the control parameters from the AP 18: then 19. goto 1: $20 \cdot$ end if 21: end loop

 Table 1
 Simulation parameters.

Simulator	ns-2(ver.2.34)
Wireless environment	IEEE802.11g
	54Mbit/s
AP buffer size	250 packets
Transport protocols	UDP, TCP
Segment size	1000 byte
TCP receiver window size	128 Kbyte
The number of flows	5, 10, 20
Simulation time	60 s



the network simulator ns2 [29].

4.1 Simulation Settings

Table 1 and Fig. 2 show simulation parameters and the simulation model. This network used IEEE802.11g (PHY) [17] for the wireless LAN environment, and SP-MAC was implemented in all wireless terminals. We assumed that none of the terminals were moved. In this model, we considered the case in which wireless terminals were the senders and generated 60 seconds of traffic (each wireless terminal generated one flow). Next, we used UDP and TCP for the transport protocol and TCP-Reno with Sack (the basic control) and CUBIC-TCP (the standard of Linux and Android OS) for TCP version. All wireless terminals were always sending data, and the sending rate of UDP was 30 Mbit/s. Each TCP

Table 2The number of collisions for each flow (UDP).

The number of flows	CSMA/CA	SP-MAC
5	55234.9	1.0
10	94796.6	3.2
20	135802.5	10.2

 Table 3
 The number of collisions for each flow (TCP-Reno with Sack).

The number of flows	CSMA/CA	SP-MAC
5	17632.2	0
10	32554.5	0
20	42999.0	0

 Table 4
 The number of collisions for each flow (CUBIC-TCP).

The number of flows	CSMA/CA	SP-MAC
5	18446.9	0
10	56168.3	0
20	75248.9	1.4

flow sent data using FTP. The simulation results showed averages of 10 trials. This study evaluated the number of data frame collisions and the total throughput determined by receipt data at the receiver terminal.

In SP-MAC, we set the control parameters [30] as follows by considering the synchronization condition (see Sect. 2.2). First, the initial phase $\theta_i(0)$ and natural frequency ω_i were set to non-overlapped values in the range of (0, 1.0) and [0, 2.0], respectively. Then, we set the coupling strength K to 5 by considering Eq. (4) and Eq. (5), such that it was larger than the critical coupling strength K_c . The control interval Δt was set to 10 ms. In this condition, for N = 20, the convergent amplitude R and frequency Ω in the mean field were 0.993 and 1.05, respectively. Thus, using these parameters, all wireless terminals synchronized with phase shifting.

4.2 Simulation Results

First, for basic evaluations, we compare SP-MAC to the original CSMA/CA. Then, we show the comparative evaluations between SP-MAC and the typical existing methods for collision avoidance (PCF in IEEE802.11, TDMA, and Semi-Random Backoff (SRB) [13]). Next, this paper presents the results under the scenario where both SP-MAC and CSMA/CA exist. Finally, we show the results when join and leave wireless terminals exist.

4.2.1 Basic Performance Evaluations

First, this section shows the number of data frame collisions. Tables 2, 3, and 4 show the results of UDP, TCP-Reno with Sack, and CUBIC-TCP when the number of flows changes from 5 to 20, respectively. From Tables 2, 3, and 4, the number of data frame collisions increases with the number of flows, as in the case of the original CSMA/CA. This occurs because the initial back-off time tends to conflict easily when the number of flows increases. In particular, because

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Fig. 3 The total throughput for each flow (UDP).



Fig. 4 The total throughput for each flow (TCP-Reno with Sack).

UDP always uses a higher transmission rate (30 Mbit/s) than that of TCP, it has the largest number of collisions. On the other hand, SP-MAC can drastically reduce the number of data frame collisions in all the transport protocols. In SP-MAC, the collisions only occur at the beginning of data transmission. For example, for 20 UDP flows, the collisions occur from 0 to 2 s. The Kuramoto model requires a specific amount of time for synchronization, and the convergence time is around 2 s in this environment. Consequently, if the transmission rate is always high as with UDP, the collisions occur at the beginning of data transmission. Moreover, in TCP-Reno with Sack and CUBIC-TCP, the collisions rarely happen, compared with UDP, because TCP controls the transmission rate. In addition, because TCP-Reno with Sack usually has a lower congestion window size than CUBIC-TCP, no collisions occur in this environment. Therefore, it is confirmed that collisions rarely happen using SP-MAC even when the number of flows increases.

Next, this paper shows the total throughput. Figures 3, 4, and 5 plot the total throughput of UDP, TCP-Reno with Sack, and CUBIC-TCP when the number of flows changes from 5 to 20, respectively. From Figs. 3, 4, and 5, SP-MAC can obtain higher throughput than the original CSMA/CA method. In the case of UDP and CUBIC-TCP, the through-



Fig. 5 The total throughput for each flow (CUBIC-TCP).

put of the original CSMA/CA method tends to decrease as the number of flows increase. UDP uses a stable transmission rate of 30 Mbit/s because it does not have a rate control mechanism. Therefore, because the number of collisions increases with the number of flows, the number of received UDP segments at the receiver decreases. Consequently, the total throughput of UDP decreases. Next, CUBIC-TCP drastically increases the congestion window size at the beginning of data transmission. Therefore, if the number of flows increases, the number of transmitted data frames also drastically increases. In this situation, a TCP segment can be easily lost because a continuous collision of data frames occurs, as in the case of UDP. Therefore, the total throughput of CUBIC-TCP also decreases as the number of flows increases. In TCP-Reno with Sack, because the increment rate of the congestion window size is significantly smaller than that of CUBIC-TCP, the number of collisions is also smaller than CUBIC-TCP. As a result, the total throughput of TCP-Reno with Sack does not decrease in this environment. On the other hand, SP-MAC increases the total throughput as the number of flows increases in UDP, CUBIC-TCP, and TCP-Reno with Sack cases. This is because SP-MAC can drastically decrease the number of collisions (see Table 2, Table 3, and Table 4), and the idle time of the channel decreases as the number of flows increases. In addition, because the AP sends data (TCP-ACK) in Figs. 4 and 5, they show the case when the downlink flow coexists with the uplink flow. Therefore, these results indicate that SP-MAC can support the coexistence of both the uplink and downlink flow.

If the collision causes data loss, the difference of the congestion window size among TCP flows increases. Then, the throughput becomes unfair [31] among uplink (from the wireless terminal to AP) TCP flows in the wireless LAN (CSMA/CA). However, because SP-MAC can drastically reduce the number of collisions, it is possible to solve the throughput unfairness. Thus, we evaluated the throughput of each flow and determined whether SP-MAC could obtain the fairness. Figure 6 shows the standard deviation of each flow when TCP version is CUBIC-TCP. As shown in Fig. 6, the standard deviation of the original CSMA/CA method in-



Fig. 6 The standard deviation of each flow (CUBIC-TCP).



Fig.7 The total throughput of UDP for each flow when comparing SP-MAC to PCF, TDMA, and SRB.

creases when the number of flows increases from 5 to 10. Therefore, the difference of throughput among TCP flows increases because the difference of the congestion window size between the collision terminal and collision-free terminal increases. On the other hand, as mentioned above, in SP-MAC, collisions hardly occur when all flows use the access interval based on the synchronized oscillators. Therefore, even if the number of flows increases, all flows can obtain almost the same congestion window size. Consequently, the throughput of all flows becomes almost the same. Therefore, it is clear that SP-MAC can obtain throughput with more TCP fairness than the original CSMA/CA method.

4.2.2 Comparative Evaluation with Existing Method for Collision Avoidance

This section compares SP-MAC to the existing methods for collision avoidance. We used PCF in IEEE802.11 because PCF can avoid collisions and coexist with CSMA/CA (DCF) in the same manner as SP-MAC. In addition, this study used TDMA because it can completely avoid collisions and have lower overhead using the time scheduling. Furthermore, we used Semi-Random Backoff (SRB) because it is based on CSMA/CA and can avoid collisions effectively.



Fig.8 The rate of the sum of receipt control frame size and management frame size compared to total receipt frame size.

Fig. 7 plots the total throughput of UDP for each flow. In TDMA, the slot time is allocated for all wireless terminals, including the AP, and one slot time is set equal to the time required for sending one data frame. As shown in Fig. 7, PCF can obtain a higher total throughput than the CSMA/CA when the number of wireless terminals becomes larger than 10 (i.e., the collisions often occur) because it can avoid the collisions of data frames by polling. However, the total throughput of PCF decreases as the number of flows increases. Because PCF is the option function in IEEE802.11, the contention-free period of PCF and the contention period of DCF are continuously repeated. In the contention-free period, there are no collisions. On the other hand, the contention period has collisions. Therefore, the contention period decreases the total throughput of the PCF case as the number of flows increases. On the other hand. SP-MAC can drastically reduce collisions (see Table 2). Therefore, the total throughput of SP-MAC is larger than that of PCF. Additionally, the total throughput of SRB is also larger than that of PCF and CSMA/CA because it can avoid collisions effectively. However, SP-MAC can obtain higher total throughput than SRB. It is because that the average back-off time of SRB is larger than that of SP-MAC. SRB uses the deterministic value for the back-off time after successful transmission using the random value. Therefore, because SRB uses a binary increase of CW after collisions, the average back-off time becomes larger when the deterministic value is set after collisions. On the other hand, SP-MAC does not use the binary increase even if the collisions occur. As a result, the total throughput of SP-MAC is larger than that of SRB. Next, TDMA has the highest throughput because there is no collision using the time scheduling and it does not require the ack frame transmission for confirming successful data transmission. Thus, TDMA result shows the maximum performance in this environment. In this case, we found that SP-MAC can obtain higher throughput than CSMA/CA, PCF, and SRB. Therefore, SP-MAC can achieve the closest value against the maximum performance of TDMA.

Next, Fig. 8 shows a rate of the sum of receipt control frame size (ack and poll) and management frame size (beacon) compared to total receipt frame size. That is, Fig. 8

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Fig.9 The total throughput of UDP for each flow in the unsaturated flow case.

indicates the control overhead of each method. In Fig. 8, because TDMA does not send control frame during the transmission, we only show the SP-MAC, PCF, and SRB results. As shown in Fig. 8, we found that the SP-MAC rate is smaller than that of PCF when the number of flows is larger than 10. This occurs because the total receipt frame size of PCF decreases by collisions of data frames as the number of flows increases. Furthermore, the receipt control frame size and management frame size for polling (poll and beacon) does not decrease because collisions of control frames hardly occur using short IFS time. As a result, the rate of control frame size increases when the number of flows increases. On the other hand, SP-MAC does not increase collisions, even if the number of flows increases. In addition, SP-MAC does not send any control frames to avoid collisions during data transmission. Thus, because the number of receipt data frame is usually the same as that of an ack frame, the rate of receipt control frame size and management frame size does not increase even if the number of flows increases. Therefore, the rate of SP-MAC is smaller than that of PCF. Furthermore, we confirmed that the control overhead of SP-MAC is almost same as that of SRB.

For the situation shown in Fig. 7, we assume the saturated flow case; all wireless terminals always have data for transmission. However, it is expected that each flow does not always send data (unsaturated flow). Therefore, we show the throughput of an unsaturated flow case. Figure 9 plots the total throughput of UDP for each flow in the unsaturated flow case, where the number of flows is 5. In this evaluation, each wireless terminal has a data transmission time and an idle one, and these values have the exponential distribution with mean Δt (in the range of [100, 5000]ms). In Fig. 9, the x-axis duration indicates Δt (this value is different from the control interval of SP-MAC). As shown in Fig. 9, we found that SP-MAC can obtain the best throughput in the unsaturated flow scenario. Because SP-MAC has lower collisions than CSMA/CA and PCF, the throughput of SP-MAC is larger than that of CSMA/CA and PCF. In addition, because the average back-off time of SP-MAC is smaller than that of SRB, the total throughput of SP-MAC is lager than that of SRB. On the other hand, the throughput



Fig.10 The total throughput of UDP when both SP-MAC and CSMA/CA exist.

of TDMA decreases as the duration increases. This occurs because all wireless terminals do not always send data in this case. That is, if the duration increases, the unused time slot becomes larger because the wireless terminal does not always have transmission data. As a result, the throughput of TDMA decreases. Then, because SP-MAC can send data when the channel becomes idle, like CSMA/CA, SP-MAC can obtain higher throughput than TDMA. Furthermore, it is important to note that TDMA cannot simultaneously exist with CSMA/CA. On the other hand, SP-MAC can simultaneously exist with CSMA/CA. Thus, we will show the coexisting scenario in the next section.

4.2.3 Performance Evaluation When Both SP-MAC and CSMA/CA Exist

This section evaluates the throughput (UDP case) when both the SP-MAC and CSMA/CA terminals exist in the same WLAN system. In this evaluation, the total number of wireless terminals was always set to 20 (and remained unchanged). The number of CSMA/CA (SP-MAC) terminals, however, changed from 0 to 20. Figure 10 shows the total throughput when the number of SP-MAC and CSMA/CA terminals changes. When the number of CSMA/CA terminals was zero, only SP-MAC terminals were present. Similarly, when the number of CSMA/CA terminals was 20, no SP-MAC terminals existed. As shown in Fig. 10, the CSMA/CA terminals can achieve throughput even when the SP-MAC terminals exist because SP-MAC changes the mechanism of the back-off time calculation. Here, Fig. 11 shows the average throughput for each method. As shown in Fig. 11, we observed that the SP-MAC method can achieve higher throughput than the CSMA/CA method. This is due to the fact that SP-MAC does not use the binary increase, like CSMA/CA, when the collisions occur. That is, the back-off time of SP-MAC terminals is relatively lower than that of CSMA/CA terminals. As a result, the throughput of SP-MAC is higher than that of CSMA/CA.

In summary, we found that both SP-MAC and CSMA/CA can simultaneously communicate when the SP-



Fig. 11 The average throughput of UDP when both SP-MAC and CSMA/CA exist.

MAC terminals exist with the CSMA/CA ones. On the other hand, if the wireless LAN manager needs to consider the fairness, there is a room to improve the SP-MAC fairness. However, because the main purpose of SP-MAC is to obtain the higher throughput by avoiding the collisions when only SP-MAC terminals exist, we consider the improvement of the fairness for CSMA/CA as future work.

4.2.4 Performance Evaluation When Join and Leave Wireless Terminals Exist

In Sect. 4.2.2, we showed the results when the number of wireless terminals is fixed (static condition). However, in the real environment, it is possible that the wireless terminals dynamically join and leave. Therefore, this section shows whether SP-MAC can handle the dynamic condition well when the wireless terminals join and leave. In this evaluation, we consider a following scenario (total simulation time is 60s); To begin with, 20 wireless terminals join a network at the beginning of simulation. Next, 10 wireless terminals leave from the network at 15s. Then, 5 wireless terminals leave from the network at 25s. After that, 5 wireless terminals join the network at 35s. Finally, 10 wireless terminals join the network at 45s. In this environment, all wireless terminals always have data for transmission while they join the network. Note that each method (PCF, TDMA, SRB, and SP-MAC) changes the control parameters depending on the number of wireless terminals. Thus, these methods always use the appropriate control parameters even if the number of wireless terminals changes. Figure 12 shows the total throughput of each method when the wireless terminals dynamically join and leave. From Fig. 12, we found that the trend of total throughput of the dynamic condition is almost same as that of the static condition (see Fig. 7). Furthermore, we confirmed that the control overhead of the dynamic condition is almost same as that of the static condition in Fig. 8. Next, Fig. 13 shows the time change of total throughput. In Fig. 13, we only show the results of CSMA/CA, SRB, and SP-MAC because these methods are based on the back-



Fig. 12 The total throughput of UDP when join and leave wireless terminals exist.



Fig.13 The time change of total throughput (UDP) when join and leave wireless terminals exist (SP-MAC, CSMA/CA, and SRB).

off mechanism[†]. From Fig. 13, we found that SP-MAC and SRB can obtain the stable throughput because these methods can avoid collisions effectively. Furthermore, SP-MAC can get higher total throughput than CSMA/CA and SRB. In CSMA/CA, the total throughput increases when the number of wireless terminals decreases because the number of collisions decreases. Therefore, we confirmed that SP-MAC can handle the dynamic condition well same as the other methods when the wireless terminals join and leave.

5. Conclusion

In CSMA/CA of the IEEE802.11 wireless LAN, if the number of wireless terminals connecting to an AP increases, the number of data frame collisions increases. This occurs because the back-off time determined by the initial CW of each flow easily tends to have the same value. Therefore, this paper proposed a new MAC method, SP-MAC, based on the synchronization phenomena of coupled oscillators. SP-MAC uses the synchronized phase with phase shifting for calculating the back-off time. Moreover, simulation evaluations showed that SP-MAC can avoid collisions and improve the total throughput. In addition, because SP-MAC can drastically avoid collisions, it can effectively use the

[†]We confirmed that the trend of TDMA and PCF are almost same as that of SP-MAC and CSMA/CA, respectively.

bandwidth when the number of wireless terminals increases. Therefore, SP-MAC could become a solution for the terrible congestion in future wireless LAN networks.

Finally, the following work could be studied in the future:

- Consideration for overlapping BSS(OBSS).
- Evaluation when hidden terminals exist.
- Detailed evaluation when the uplink flow coexists with the downlink flow.
- Extension of SP-MAC to support QoS control such as IEEE802.11e.
- Evaluation using SP-MAC implementation in a real environment.

Acknowledgments

This work was partly supported by JSPS KAKENHI Grant Numbers 24560471, 26420367, 26280032, Project Research Grants of the Graduate School of Information Sciences, Hiroshima City University, and the Hiroshima City University Grant for Special Academic Research.

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Hiroyasu Obata received B.E., M.E., and Ph.D. degrees in Computer Engineering from Hiroshima City University, Japan, in 2000, 2002, and 2007, respectively. From 2002 to 2003, he was with KDDI Co., Ltd. From 2003 to 2009, he was a Research Associate at Hiroshima City University. He is currently a Lecturer in the Graduate School of Information Sciences, Hiroshima City University. His interests include computer communications on wireless networks, such as satellite links, wireless

LANs, access control, and high speed transport protocols. He received the Information Network Research Award of IEICE in 2015. Dr. Obata is a member of IEEE (U.S.A) and IPSJ (Japan).



Ryo Hamamoto received B.E. and M.E. degrees in Computer Engineering from Hiroshima City University, Japan, in 2012 and 2014, respectively. His research interests lie in the area of wireless networks and distributed systems. He received the Information Network Research Award of IEICE in 2012 and 2015. Mr. Hamamoto is a student member of IEEE (U.S.A).



Chisa Takano received a B.E. degree in Telecommunication Engineering from Osaka University, Japan, in 2000, and a Ph.D. in System Design Engineering from Tokyo Metropolitan University, Japan, in 2008. In 2000, she joined the Traffic Research Center, NTT Advanced Technology Corporation (NTT-AT). Since April 2008, she has been an Associate Professor of the Graduate School of Information Sciences, Hiroshima City University. Her research interests lie in the area of computer

networks and distributed systems. She received the IEICE's Young Researchers' Award in 2003. She received the Information Network Research Award of IEICE in 2004, 2012, and 2015. Dr. Takano is a member of IEEE (U.S.A).



Kenji Ishida received B.E., M.Sc., and Ph.D. degrees from Hiroshima University, Japan, in 1984, 1986, and 1989, respectively. He was at Hiroshima Prefectural University from 1989 to 1997. From 1997 to 2003, he was an Associate Professor at Hiroshima City University. Since 2003, he has been a Professor in the Department of Computer Engineering, Faculty of Information Sciences, Hiroshima City University. His interests include distributed computing systems and designing control procedures

for computer networks. He received the Information Network Research Award of IEICE in 1998, 2000, 2012, and 2015. Dr. Ishida is a member of IEEE (U.S.A.), ACM (U.S.A.), and IPSJ (Japan).